

Inflation with improved D3-brane potential and the fine tunings associated with the model

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We revisit our earlier investigations of the brane-antibrane inflation in a warped deformed conifold background, reported in [21], where now we include the contributions to the inflation potential arising from imaginary anti-self-dual (IASD) fluxes including the term with irrational scaling dimension discovered recently in [26]. We observe that these corrections to the effective potential help in relaxing the severe fine tunings associated with the earlier analysis. Required number of e-folds, observational constraint on COBE normalization and low value of the tensor to scalar ratio are achieved which is consistent with WMAP seven years data.

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I. INTRODUCTION

Cosmological inflation [1] is a mechanism, for the universe to undergo a brief period of accelerated expansion. This is postulated to cure some of the intrinsic problems of the hot big-bang model. The inflationary scenario not only explains the large-scale homogeneity of our universe but also provides a way, via quantum fluctuation, to generate the primordial inhomogeneities which is the seed for understanding the structure formation in the universe. Such inhomogeneities have been observed as anisotropies in the temperature of the cosmic microwave background. The inflationary paradigm has stood the test of observational and theoretical challenges in past two decades [2, 3].

Inflation can be implemented using a single scalar field slowly rolling over the slope of its potential. However, the initial conditions for inflation and the form of the potential function are expected to come from a fundamental theory of gravity and not to be chosen arbitrarily. In this context, enormous amount of efforts are underway to derive inflationary models from string theory, a consistent quantum field theory around the Planck's scale and considered to be ultraviolet-complete theory of gravity. Discovery of D-branes, gauge/gravity duality and various nonperturbative aspects in string theory have also played crucial role in building and testing inflationary models of cosmology.

In past few years, many inflationary models have been constructed from string theory compactified to four dimensions where D-branes have played the most important role. The examples are inflation due to tachyon condensation on a non-BPS brane, inflation due to the motion of a D3-brane towards an anti-D3-brane [4–7], inflation due to geometric tachyon arising from the motion of a probe brane in the background of a stack of either NS5-branes or the dual D5-branes [8]. Another attempt has been made in [9] where higher curvature corrections and a dynamical dilaton has been included in the effective action for generating dark energy. However, these models do not take into account the details of compactification and the effects of moduli stabilization. Such issues could be addressed only when it was learnt [10] that the background fluxes sourced by D3 and D5-branes can stabilize the axio-dilaton and the complex structure moduli of type IIB string theory compactified on an orientifold of a Calabi-Yau threefold. Moreover, the back reaction of these D-branes yields the geometry of a throat [11] which could be glued smoothly to the compact Calabi-Yau manifold. Further important progress was achieved when it was shown in Ref. [12] that the Kähler moduli fields also can be stabilized by a combination of fluxes and nonperturbative effects via gauge dynamics of either an Euclidean D3-brane or from a stack of D7-branes, wrapping super-symmetrically a four cycle of the compact manifold, placed around the base of the throat.

The above results enabled to construct an inflationary model [13] which took account of the compactification data (see also Refs. [14]) since the inflaton potential is obtained by performing string theoretic computations involving the details of fluxes and warping. In this scenario inflation is realized by the motion of a D3-brane, placed in the compact manifold, towards a distant static anti-D3-brane sitting at the tip of the throat. The radial separation between the two is considered to be the inflaton field. The effect of the moduli stabilization resulted in a large mass to the inflaton field which turned out to be of the order of Hubble parameter and hence spoils the inflation. As a possibility for circumventing this problem, it was proposed [15–17] to embed the D7-branes such that at least one of the four-cycles carrying the nonperturbative effects descend down a finite distance into the warped throat which

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implied that the probe D3-brane is constrained to move only inside the throat. This consideration lead to the inflaton potential having an inflection point. The inflation dynamics however, within a single throat model [18], revealed that when the spectral index of scalar perturbation reaches the scale invariant value, the amplitude tends to be larger than the COBE normalized value by about three order of magnitude, making the model unrealistic. Such problems could be solved if another non-inflating throat is added to the compactification procedure [19].

II. POTENTIAL FROM COMPACTIFICATION EFFECTS AND ITS IMPLICATION FOR INFLATION

The possibility of a realistic model for brane inflation, within the large volume compactification and a single throat scenario, received further attention when the authors of Ref. [20] observed that there are corrections to the inflaton potential which arise from the compactification effects in the ultra violet (UV). Thus the assumption of the D7-brane descending into the throat was relaxed. Instead, using AdS/CFT correspondence, the throat geometry (conifold) has been treated as an approximate conformal field theory with a high cut off scale M_{UV} . In this context, the position of the probe D3-brane is identified with the Coulomb branch vev of a field in the gauge theory which couples to bulk moduli fields. This coupling changes the Kähler potential and hence the inflaton potential. It was noted that the leading contribution to the inflaton potential comes from the coupling of a chiral operator with dimension $\Delta = 3/2$ in the dual gauge theory to the bulk field. Taking this contribution in to account, the full inflaton potential takes the form:

$$V(\phi) = D \left[1 + \frac{1}{3} \left(\frac{\phi}{M_{pl}} \right)^2 - C_{3/2} \left(\frac{\phi}{M_{UV}} \right)^{3/2} - \frac{3D}{16\pi^2\phi^4} \right] \quad (1)$$

where ϕ is the canonically normalized inflaton field related to the position of the D3-brane; $C_{3/2}$ is a positive constant and $D \sim 2a_0^4 T_3$. Here a_0 is the minimal warp factor at the tip of the throat and T_3 is the tension of D3-brane. Note that the third term in the above equation is the contribution coming from the compactification effect in the UV and the rest of the potential is the same as in [13].

The inflationary dynamics, using the above potential, was investigated in [21] and the reheating issue was discussed in [23]. It was observed that the parameter $C_{3/2}$ in the above potential has to be severely fine tuned for the inflation model to be consistent with the WMAP five years data [24]. This fine tuning becomes worse for the consistency with recent WMAP seven years data[25]. Moreover, the initial condition for the inflaton field value has also to be chosen, with acute fine tuning, to yield a possible maximum fiftyeight e-foldings.

On the other hand, recently the authors of Refs. [26] have performed a detailed analysis of the potential on the Coulomb branch of the conifold gauge theory taking into account of the UV effect on the probe D3 brane and have found many more corrections to the inflaton potential. The general structure of the corrections arising from UV deformations of the background take the form (See [26] for details):

$$V_c(\phi) = \sum_i C_i \frac{\phi^{\Delta_i}}{M_{UV}^{\Delta_i-4}} \quad (2)$$

where M_{UV} is a UV mass scale related to the ultraviolet location at which the throat is glued into the compact bulk. While, the constant coefficients C_i are left undetermined, the scaling dimensions Δ_i are found to be $1, 3/2, 2, 5/2, L = 2\sqrt{7} - 5/2, \dots$.

It should be noted that the parameters C_i are not directly restricted by flux compactification and Gauge/gravity correspondence. These coefficients contain information from two sources:(1) product of trigonometric function involving the five angles of $T^{(1,1)}$ space (the radial component being the inflaton, ϕ used in the paper). So these are objects whose numerical values are less than one, (2) they involve small perturbations of fields in the gauge theory side, which like in any field theory are much less than one and are not apriori fixed but can be fixed only with some dynamical process where we have some information from observation. In fact the parameters C_i are product of these two small values. Thus the only restriction we have is that they are much much less than one.

These contributions arise from various sources. For example, terms with scaling dimensions Δ_i with $i = 3/2, 2, \dots$ come from homogeneous solution (an arbitrary harmonic function on the conifold) and with $i = 1, 2, 5/2, L = 2\sqrt{7} - 5/2, \dots$ come from inhomogeneous solutions sourced by fluxes. The term with scaling dimension $2\sqrt{7} - 5/2$ corresponds to a flux perturbation dual to a non-chiral operator which is generically present but is not captured via perturbations of the superpotential.

In what follows, we reinvestigate the inflation dynamics by including these new corrections with the hope that the problems as mentioned earlier can be cured namely to examine the flexibility in the space of parameters to obtain the

required number of e-foldings and other consistency of the inflation dynamics. In fact we find that these corrections not only help in constructing a viable inflation model consistent with WMAP seven years data but also the fine tuning problem as mentioned above is considerably relaxed. We can easily obtain sixty e-foldings and even more without being too tight in the choice of initial conditions and numerical values of the parameters. For this purpose, we write the full inflaton potential, including V_c as given above, as follows:

$$\mathcal{V} = \mathcal{D} \left[1 - C_1 x - C_{3/2} x^{3/2} + \left(\frac{\alpha^2}{3} - C_2 \right) x^2 - C_{5/2} x^{5/2} - C_L x^L - \frac{3\mathcal{D}}{16\pi^2 \alpha^4 x^4} \right] \quad (3)$$

where $x = \phi/M_{UV}$, $\mathcal{V} = V/M_{UV}^4$, $\mathcal{D} = D/M_{UV}^4$ and $\alpha = M_{UV}/M_{pl}$ and $L = 2\sqrt{7} - 5/2$. Let us note that as we are dealing with a small field inflation model, we only retain terms up to $\Delta = 2\sqrt{7} - 5/2$ as other contributions are insignificant. In what follows, we shall consider the inflationary dynamics of the field with the modified potential given by (3).

III. SLOW ROLL INFLATION

In this section, we shall study the dynamics of inflation based upon the improved D-brane potential and demonstrate that the model under consideration based upon (3) performs much better than the earlier model given by (1). The modified potential allows to easily generate enough inflation without involving the fine tuning of initial conditions for slowly rolling inflaton. The corrected potential also allows to decrease the fine tuning of model parameters present in (1) in a significant fashion, as we show below.

For the sake of convenience, let us cast the evolution equation for the field, $\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$ and the Friedmann equation $H^2 = \left(\frac{\dot{\phi}^2}{2} + V(\phi) \right) / 3M_{pl}^2$ in the autonomous form

$$\frac{dx}{dN} = \frac{y}{\mathcal{H}} \quad (4)$$

$$\frac{dy}{dN} = -3y - \frac{1}{\mathcal{H}} \frac{d\mathcal{V}}{dx} \quad (5)$$

$$\mathcal{H}^2 = \frac{\alpha^2}{3} \left(\frac{1}{2} y^2 + \mathcal{V}(x) \right) \quad (6)$$

where $y = \dot{\phi}/M_{UV}^2$, $\mathcal{H} = H/M_{UV}$, and N designates the number of e-foldings. In the scenario under consideration, the mobile D3-brane moves towards the anti-D3-brane located at the tip of the throat corresponding to $x = 0$ and thus we have $0 < x < 1$ since $\phi < \phi_{UV} \sim M_{UV}$.

The slow roll parameters for the generic field range are

$$\epsilon = \frac{1}{2\alpha^2} \left(\frac{\mathcal{V}_{,x}}{\mathcal{V}(x)} \right)^2 \simeq \frac{1}{2\alpha^2} \left[2 \left(\frac{\alpha^2}{3} - C_2 \right) x - C_1 - \frac{3C_{3/2}}{2} x^{1/2} - \frac{5}{2} C_{5/2} x^{3/2} - LC_L x^{L-1} + \frac{3\mathcal{D}}{4\pi^2 \alpha^4 x^5} \right]^2 \quad (7)$$

$$\eta = \frac{1}{\alpha^2} \frac{\mathcal{V}_{,xx}}{\mathcal{V}(x)} \simeq \frac{1}{\alpha^2} \left[2 \left(\frac{\alpha^2}{3} - C_2 \right) - \frac{3C_{3/2}}{4x^{1/2}} - \frac{15}{4} C_{5/2} x^{1/2} - 2LC_L x^{L-2} - \frac{15\mathcal{D}}{4\pi^2 \alpha^4 x^6} \right] \quad (8)$$

The COBE normalization and the spectral index are given by

$$\delta_H^2 \simeq \frac{1}{150\pi^2 M_P^4} \frac{V}{\epsilon} = \frac{\alpha^4}{150\pi^2} \frac{\mathcal{V}}{\epsilon} \quad (9)$$

$$n_s = 1 + 2\eta - 6\epsilon \quad (10)$$

In Fig.1, we plot the effective potentials given by (1) and (3) for a possible choice of parameters. It is clear from the figure that the introduction of new terms in model (3), it is possible to flatten the potential in the field range of

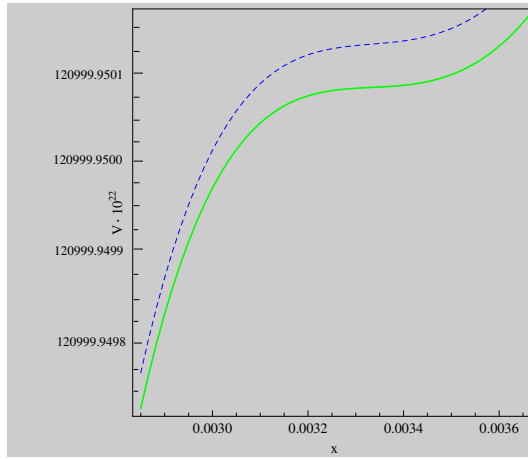


FIG. 1: The dashed line shows the plot of the effective potential given by (1) for $C_{3/2} = 0.006232$, $\alpha^{-1} = 2.11869$, $\mathcal{D} = 1.21 \times 10^{-17}$ whereas the solid line is the plot of the effective potential given by (3) for $C_1 = 10^{-7}$, $C_{3/2} = 0.006232$, $\alpha^{-1} = 2.11869$, $C_2 = 10^{-6}$, $C_{5/2} = C_L = 2 \times 10^{-5}$, $\mathcal{D} = 1.21 \times 10^{-17}$

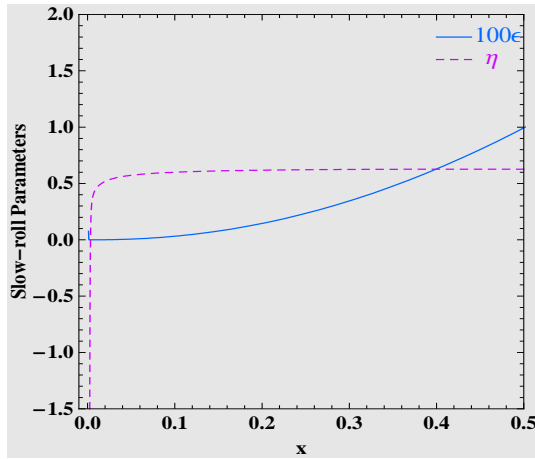


FIG. 2: Plot of the slow roll parameters ϵ & η for the effective potential (3) for the same set of parameters as in Fig. 1

interest where inflation takes place. This feature of the new potential effects the evolution of the inflaton field and hence the inflation dynamics in a considerable manner.

We further note that the slow roll parameters satisfy the relation $|\epsilon| < |\eta|$, in the case under consideration, for the field range of interest as plotted in Fig.2. Thus it is sufficient to consider the parameter η for discussing the slow roll conditions and the end of inflation. Note that the field potential should be monotonously increasing function of x to ensure realistic motion of D-brane, i.e., it should be allowed to move towards the origin (tip of the throat) where the anti-D3-brane is placed.

However, in general, the potential function can be monotonously increasing, decreasing or even can acquire a minimum for $0 < x < 1$ depending upon the numerical values of the model parameters. Thus the requirement that it should be increasing imposes constraints on the parameters of the model. Moreover these constraints on parameters should allow us to have at least sixty e-foldings as well as should meet the experimental bounds on various cosmological observables.

As reported in [21], the model described by (1) exhibits sensitivity with respect to the two parameters it has, namely, $C_{3/2}$ and \mathcal{D} and it extremely fine tuned with respect the initial values of the inflaton field x_i . The monotonicity of $\mathcal{V}(x)$ can be ensured provided we require smaller and smaller values of $C_{3/2}$. This is because we need to avoid the occurrence of a minimum of the potential as we move towards the origin before the effect of Coulomb term could become dominant. For numerical values of $\mathcal{D}^{1/4} \sim 10^{-4}$ required for observational constraints to be satisfied, we find numerical values of $C_{3/2}$ not only much smaller than one but also need to be acutely fine tuned. The field range viable for inflation turned out to be very narrow resulting in number of e-foldings to be about 60 with the initial

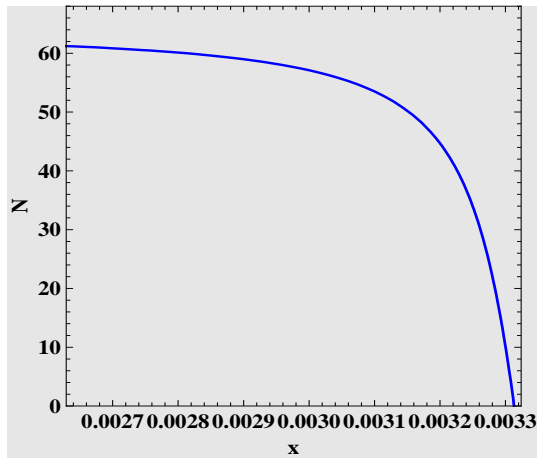


FIG. 3: Plot of the number of e-folds for the effective potential (3) versus x . The numerical values of model parameters is same as in Fig 1

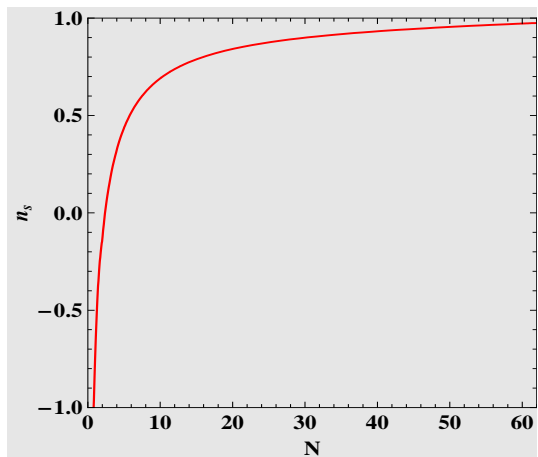


FIG. 4: Plot of the spectral index n_s versus the field number of e-folds starting from the end of inflation for the effective potential (3). For the set of parameters as in Fig 1, n_s reaches the observed value for $N \simeq 60$.

value of the field x_i being fine tuned typically to the level of one part in 10^{-7} . Any deviation of numerical values of x_i ($x_i = 0.0033050$) [21] beyond the said accuracy makes the inflaton hit the singularity before it could make the required number of e-folds. As a result, the inflationary scenario based upon the effective potential (1) becomes heavily constrained.

To make the inflation model, at least a semi-realistic one and free from severe fine tune tunings, we turn to the case of the improved effective potential given by (3). As we will see, the fine tuning of the parameters as well as that of the initial condition could be reduced. However, one might think that this is achieved at the cost of four new terms in the potential with corresponding free parameters. This is indeed true; nevertheless, it should be kept in mind that these new correction terms are not inspired by phenomenological considerations but are rigorously derived using the formalism of flux compactification and Gauge/Gravity correspondence.

As pointed out by McAllister [22], if we restrict to operators with dimension 4 for perturbation in the gauge theory side, there are 324 terms contributing to inflation potential. However, since the inflation is taking place for very small values of the field (x in our notation) and accompanied by parameters which are also much less than one, terms involving higher powers of x can be safely neglected. The x^2 term actually plays the crucial role since it affects the slow roll parameter (η). The terms with powers less than 2 play an important role in solving the eta-problem and

maintaining the flatness of the potential to give at least sixty e-foldings. We kept the term with irrational power $(2\sqrt{7} - 5/2)$ of the field for curiosity and to emphasize the fact that such a term appears in the potential. Thus keeping the term x^3 in the potential would not change our analysis and the result except for allowing some more freedom with an extra parameter. The inclusion of new terms extends the range of flatness allowing us to generate upto 70 or more e-foldings without fine tuning of the initial position of inflaton. The extra flat region is difficult to show on the plot clearly. Our numerics clearly confirms it. The later is the major contribution of the extra terms in the potential.

Our investigation shows that the numerical values of the new constants are robust and can be varied over wide range with the observational constraints satisfied. However, we should point out that with many parameters in the potential, it is difficult to scan the parameter space and put bounds on each of them. The best we have achieved is to find a set of parameters by trial and error method to satisfy the observational constraints coming from WMAP seven years data [25] and then to examine how robust the set is. Table.I and Table.II, represents such a collection of data points corresponding to different values of α^{-1} .

C_1	$C_{3/2}$	α^{-1}	C_2	$C_{5/2}$	C_L	\mathcal{D}	n_s	δ_H^2
10^{-7}	623.2×10^{-5}	2.11869	10^{-6}	2×10^{-5}	2×10^{-5}	1.21×10^{-17}	0.976	2.38×10^{-9}
1.9×10^{-7}	623.2×10^{-5}	2.11869	10^{-6}	2×10^{-5}	2×10^{-5}	1.21×10^{-17}	0.950	2.45×10^{-9}
10^{-7}	623.3×10^{-5}	2.11869	10^{-6}	2×10^{-5}	2×10^{-5}	1.21×10^{-17}	0.951	2.50×10^{-9}
10^{-7}	623.2×10^{-5}	2.11890	10^{-6}	2×10^{-5}	2×10^{-5}	1.21×10^{-17}	0.952	2.43×10^{-9}
10^{-7}	623.2×10^{-5}	2.11869	10^{-10}	2×10^{-5}	2×10^{-5}	1.21×10^{-17}	0.977	2.34×10^{-9}
10^{-7}	623.2×10^{-5}	2.11869	10^{-6}	10^{-4}	2×10^{-5}	1.21×10^{-17}	0.976	2.38×10^{-9}
10^{-7}	623.2×10^{-5}	2.11869	10^{-6}	2×10^{-5}	10^{-10}	1.21×10^{-17}	0.962	2.39×10^{-9}
10^{-7}	623.2×10^{-5}	2.11869	10^{-6}	2×10^{-5}	2×10^{-5}	1.209×10^{-17}	0.963	2.37×10^{-9}

TABLE I: A possible variation of model parameters consistent with observational bounds: $\delta_H^2 = (2.349 - 2.529) \times 10^{-9}$ & $n_s = 0.949 - 0.977$ (WMAP + BAO + H_0)(Tensor to scalar ratio of perturbations is low in the model and does not impose constraints on the model parameters)

C_1	$C_{3/2}$	α^{-1}	C_2	$C_{5/2}$	C_L	\mathcal{D}	n_s	δ_H^2
10^{-7}	3.63×10^{-3}	3	10^{-4}	2×10^{-5}	10^{-3}	10^{-17}	0.977	2.35×10^{-9}
10^{-7}	3.62×10^{-3}	3	10^{-5}	2×10^{-5}	10^{-3}	10^{-17}	0.965	2.3×10^{-9}
10^{-9}	4.50×10^{-3}	4	10^{-6}	2×10^{-7}	10^{-6}	2×10^{-17}	0.965	2.3×10^{-9}
10^{-9}	4.50×10^{-3}	4	10^{-5}	2×10^{-6}	10^{-6}	2×10^{-17}	0.96	2.34×10^{-9}

TABLE II: A set of other possible variation of model parameters, showing the flexibility of $C_{3/2}$, consistent with observational bounds.

We find that the effective potential incorporating the additional corrections is flatter over a generic range of field value for a set of numerical values of model parameters. The later relaxes the fine tuning of initial conditions for slow roll inflation and allows to obtain the required number of sixty e-foldings and even more, see Fig.3. In this case the initial value of the field x_i needs to be fine tuned only to the level of one part in 10^{-4} . In the Table I , we display a collection of sets of the numerical values of the parameters that result from the numerical search consistent with the observationally allowed range of values of density perurbations δ_H^2 , n_s and tensor to scalar ratio of perturbations. We vary one parameter at a time, keeping the other parameters fixed with numerical values as given . In Table II, we present another viable set of model parameters corresponding to numerical values of α different from those used in Table I. We have confirmed that the new set of parameters can also give rise to required number of e-folds and is consistent with observations. Note that the fine tuning associated with $C_{3/2}$ improves by one order of magnitude as compared to the earlier analysis based upon (1). In view of the above discussion, one might expect enormous improvement with regard to COBE normalization *a la* \mathcal{D} . Actually, the improvement in this case is not beyond one order of magnitude which is related to the fact that \mathcal{D} appears in the effective potential in a non-trivial way i.e. besides being an over all factor, it also appears in the Coulomb term. Hence, any change in the numerical value of \mathcal{D} crucially effects the values of other parameters subject to the observational constraints. In Fig.4, we have shown the spectral index versus the number of e-folds for a the same choice of parameters as used in Fig.1.

IV. CONCLUSIONS

In this paper, we have investigated an inflationary model based upon an effective D-brane potential (3) that includes corrections to the potential arising from imaginary anti-self-dual fluxes encoded by terms containing coefficients $C_1, C_2, C_{5/2}$, and C_L . In [21], where these terms were absent, it was observed that the monotonicity of the potential imposes tough constraints on $C_{3/2}$. It needed to be fine tuned to the level of one part in 10^{-7} for observational constraints to be satisfied. The potential was flat near the origin for a very narrow field range and that too for only restricted values of model parameters. The constant \mathcal{D} required heavy fine tuning to satisfy the COBE constraint and the observational data on the spectral index n_s . What was worse, the initial condition for the inflaton required fine tuning at the level of one part in 10^{-6} otherwise the inflaton rolls to the region of instability before it completes 60 e-folds. The latter is related to very narrow field range of flatness of the potential (1). In the present model, there are more parameters (corresponding to the corrections due to imaginary anti-self-dual fluxes) in the potential (3) which allow to increase the range of flatness of the potential around $x = 0$ thereby relaxing the fine tuning of initial conditions of the inflationary dynamics. The modified D-brane potential can easily give rise to a large number of e-foldings without invoking much fine tuning of initial conditions of the inflaton which is one of the major advantages of new correction terms in the effective D-brane potential. As for the new constants, they do not involve much fine tuning for observational constraints to be satisfied. The fine tuning of model parameters $C_{3/2}$ and \mathcal{D} also improves by one order of magnitude respectively in the scenario based upon the corrected potential. Thus the inflationary scenario based upon the corrected potential performs much better than the earlier models of D-brane inflation. However, it should be noted that we have retained only five terms in the effective potential out of 324 terms dictated by string theoretic considerations. It would be interesting to investigate the impact of other terms on the dynamics of inflaton. Secondly, our search of parameter space was based upon hit and trial method. The more sophisticated method based upon Monte-Carlo method could give rise to larger parameter space.

Last but not least, a viable inflation should be followed by a successful reheating. Reheating in the scenario under consideration, could occur at the time of collision of D-brane with the \bar{D} -brane located at the tip of the throat which is beyond the regime of perturbative string theoretic frame work used to obtain the effective potential (3). From phenomenological considerations, it looks quite plausible to implement here the instant reheating mechanism suitable to the class of models of non-oscillatory type. Since the new corrections to the D-brane potential are insignificant in the region where inflation ends, the preheating temperature is of the same order as obtained in case of the effective potential (1) [23].

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